Impact of pressure on high intensity colorless distributed combustion

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HIGHLIGHTS

- Examined the impact of pressure on performance in distributed combustion.
- Lower velocity at higher density and pressure results in inadequate mixing.
- NO increased and CO decreased with pressure and residence time.
- NO increased marginally with increase in pressure at given residence time.
- Ultra-low emissions at high pressures under distributed combustion condition.

ABSTRACT

In recent years, colorless distributed combustion (CDC) has been shown to provide ultra-low pollutants emission, enhanced stability, fuel flexibility and thermal field uniformity. To achieve CDC conditions, fuel–air mixture must be properly prepared prior to the mixture ignition. In this paper, the impact of moderate pressure increase on a test combustor is examined with emphasis on pollutants emission under near CDC conditions. Increase in pressure at constant mass flow rate resulted in a significant increase in NO emission and departure from CDC conditions. This is a result of reduction of the volume flow rate and injection velocity with pressure increase, as well as an increase in the apparent residence time of gases within the combustor. These conditions led to less than adequate mixing and more residence time of gases in the post flame zone to form NO_x. CO emissions were reduced as longer residence time allowed for complete conversion of CO to CO_2. Also, the increase in pressure enhanced chemical kinetics and suppressed dissociation. Increasing the combustor pressure with constant heat release intensity, where mass flow rates are increased to keep the apparent residence time constant, showed a slight increase (1 PPM) of NO under premixed conditions and significant reduction of CO. OH* chemiluminescence showed that the reaction zone did not change with increase in pressure under premixed combustion. For non-premixed combustion, the reaction zone intensity increased and was more concentrated with increase in pressure to result in higher emissions as compared to the premixed case. In both cases, CO emission was significantly reduced due to the increased heat load and temperatures within the combustor. Relations describing change of NO and CO emissions with pressure were used to predict the combustor emissions at higher pressures. Difference between premixed and non-premixed modes revealed the need for more adequate mixing, necessary for CDC condition. Increase in pressure without considering flow velocities and flowfield can lead to departure from CDC conditions with simultaneous increase in emissions.

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1. Introduction

Increased concern on future energy in terms of energy security and environmental impact have motivated engineers to look for new and novel methods to furnish our energy needs in a sustainable way with minimal impact on the environment. In this aspect, combustion engineers have focused on finding new combustion techniques that minimize pollutants emission (such as oxides of nitrogen, carbon monoxide, unburned hydrocarbon, and soot), and develop fuel flexibility for combustors using fossil fuels and renewable biofuels, while maintaining high conversion (combustion) efficiency. Other important performance factors include alleviation of combustion instability, enhance thermal field uniformity (pattern factor), and reduce combustion noise and pressure drop across the combustor. In recent years, multiple new combustion

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technologies have emerged that address the above concerns on performance. Amongst the most promising technologies are colorless distributed combustion (CDC) [1–3], flameless oxidation (FLOX) [4,5], and moderate or intense low-oxygen dilution (MILD) [6]. From these technologies, colorless distributed combustion (CDC) has presented itself as a new combustion method that offers ultra-low emission, high combustion efficiency, high combustion stability, and enhanced thermal field uniformity. CDC incorporates some of the same principles of high temperature air combustion (HiTAC) that has demonstrated ultra-low emissions, uniform thermal field, and significant energy gains for furnace application [7]. In HiTAC, low oxygen concentration air at normal temperature is used for combustion with the air preheated to high temperatures prior to the ignition of fuel. The temperature of combustion gases in the furnace is only about 50–100 °C higher than that of the preheated low oxygen concentration air just prior to ignition. The oxygen concentration in the incoming combustion air is generally very low (only about 2–5% by volume, depending on the application). Increase in incoming air temperature has been achieved through enthalpy exchange with the hot exit gases or via internal enthalpy exchange [7]. In CDC, increase in temperature of the fresh mixture stream is achieved through internal recirculation of hot reactive species from within the combustor. This internal recirculation not only increases the fresh reactants temperature but also decreases oxygen concentration to result in low oxygen high temperature mixture prior to ignition and combustion of the fuel. This combination of high temperature and low oxygen concentration results in a distributed reaction, wherein the reaction zone occupies a larger volume at a lower reaction rate (from high temperature of the reactants). This low reaction rate over large reaction volume results in the same fuel consumption and reaction as normal combustion. However the benefits include combustor operation at lower equivalence ratios, low temperature rise, and elimination of thermal non-uniformities. This design method helps to mitigate thermal NO_x formation and emission produced from the Zeldovich thermal mechanism [8].

Adequate and fast mixing between the fresh reactants and recirculated hot reactive species is critical to achieve distributed combustion conditions. Different geometries have been investigated including swirling and non-swirling configurations with focus on pollutants emission [1] and isothermal flowfield [9]. Swirling combustor geometry that demonstrated the lowest NO and CO emissions also had the highest recirculation ratio in the geometries examined [9]. These conditions have established the impact of internal recirculation of hot reactive species on seeking designs for ultra-low emissions. Swirling motion was generated through tangential air entry rather than swirlers. Different air and fuel introduction scenarios have been investigated to enhance the combustion performance and foster CDC conditions. Increased air injection velocity revealed an increase in internal hot reactive species recirculation and a decrease of pollutants emission [10]. Different fuel introduction schemes have been examined with focus on mixture preparation effects prior to ignition [11]. Mixing air, fuel, and hot reactive species is challenging especially under non-premixed conditions where air and fuel are introduced separately. The difference between cross injection and co-axial injection was investigated [11] along with the increased separation between air and fuel injection points in cross flow configuration [1,11]. Early injection resulted in air and fuel ignition without proper mixing with recirculated gases while late injection led to ignition without adequate fuel–air mixing [11], leading to a diffusion flame behavior [1]. These two extremes conditions of early and late injection can lead to significant increase in emissions, specifically NO emissions, which can be avoided through proper separation between air and fuel injection location in non-premixed combustion mode [11]. Non-premixed conditions are favorable

for alleviating combustion instability. The CDC mode of combustion has been shown to alleviate combustion instability under both non-premixed and premixed combustion condition.

CDC have been extensively studied under atmospheric pressure conditions using room temperature air [1,9–10], as well as preheated air [2,11]. Various fuels examined include methane [1,2], ethanol, propane and kerosene [12], and biofuels [13]. Gas turbines combustors operate at elevated pressures and temperatures (due to heating through the compressor). The impact of inlet temperature have been studied up to 600 K (corresponding to a pressure ratio ~16), where the air inlet temperature was shown to significantly impact NO emissions [2]. However, limited data is available on CDC operation under elevated pressure conditions. Combustor operation at elevated pressure is expected to impact the reaction behavior, flowfield, residence time of gases and pollutants emission.

The impact of pressure on NO_x emissions have been numerically investigated and compared to experimental values under lean premixed conditions [14]. Rutar and Malte [14] and Steele et al. [15] found that NO_x slightly decreases with increase in pressure at constant residence time. However, NO_x, increased significantly with increase in residence time (higher than 1.5 ms) for all pressures examined. This increase in NO_x was accompanied with a sharp decrease in CO emission. Other researchers have demonstrated the impact of pressure on NO_x emission, where emissions increased with increase of pressure at low temperature (lean/rich combustion) and decreased at high temperature (near stoichiometric conditions) [16]. They also investigated the impact of unmixedness on emissions (as a result of partially premixed combustion, or departure from perfectly premixed combustion). The unmixedness (U, defined as: $f'^2/[f(1-f)]$, where f' is the fluctuation of the fuel concentration, and f is the mean fuel concentration) takes a value of zero for perfectly premixed condition and one for a perfectly unmixed injection [16,17]. The authors concluded that under perfectly premixed conditions, NO_x emission have a negative pressure exponent. However, for unmixedness levels typical of gas turbine combustors, NO_x emissions have a positive pressure exponent [16]. This investigation was limited to unmixedness of about 0.08%. Unmixedness has been also investigated under simulated gas turbine conditions, where experimentally measured NO_x emissions increased with both pressure and degree of unmixedness (up to 0.3% unmixedness) [17].

In this paper, the impact of pressure on NO and CO emissions is examined in a model combustor at an energy (heat) release intensity of 31.5 MW/m^3 atm that have relevance for stationary gas turbine applications using methane as the fuel. The impact of increase in pressure on pollutants emission is investigated. The experiments were performed while keeping the flow rates constant (thus increase of residence time). The effect of increase in pressure and flow rates (keeping the residence time constant) on pollutants emission is also examined. The results are reported under both premixed and non-premixed combustion modes with an effort to outline the combustor performance at elevated pressures. Combustor pressures were varied between 1 and 2.5 atm with view to develop a high pressure combustor for further experimentation at much higher pressures suitable for gas turbine conditions.

2. Experimental facility

The combustor performance under elevated pressure conditions was evaluated with focus on pollutants emission. The combustion chamber utilized was a cylindrical chamber with air injected tangentially at half the height of the chamber for all the cases investigated. For enhancing the residence of reactants in the combustor, a tube was extended inside the combustor for product gas exit. Fig. 1 shows a schematic diagram of the combustor used. This extended
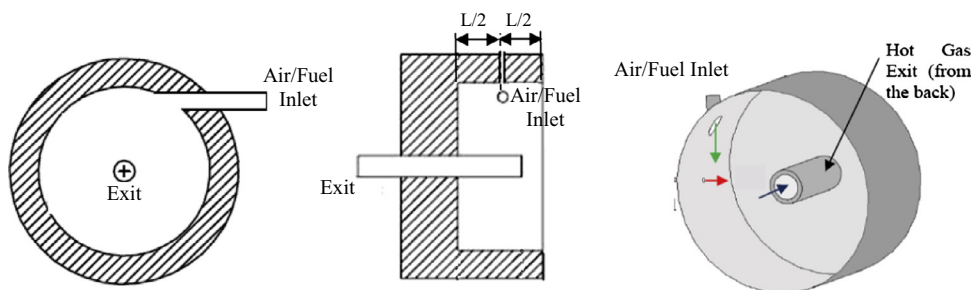
Fig. 1. Schematic diagram of the combustor with extended axial exit "ATP" (left: top section at mid location, middle: front section at cylinder axis, and right: 3D model).

tube prevents the gases from directly exiting the combustor, that is the flow is injected at the mid plane and has to move to the right before exiting at the left, rather than directly exiting from the left, see Fig. 1 (middle). More detailed description of the combustor geometry is given elsewhere [9].

Air and methane fuel flow rates were measured using choked flow orifice systems. Precision stainless steel orifices were used to choke the flow of gases with upstream pressure controlled to supply the required mass flow rate of gases. The upstream pressure was controlled using pressure regulators to maintain a steady pressure. The upstream pressure for both air and fuel was maintained between ±0.2 psi (±0.014 atm) of the desired pressure. This resulted in a flow rate accuracy of about 1%. For all experiments, the pressure downstream of the orifices was also measured to verify that choking condition existed for proper flow control at elevated pressure operation.

Detailed investigations on the overall emissions from the combustor as well as visible emissions have been performed at various experimental conditions. The concentration of NO was measured using a NO–NO$_x$ chemiluminescent gas analyzer, CO concentration using the non-dispersive infrared method and O$_2$ concentration (used to correct the NO and CO emissions at standard 15% oxygen concentration) using galvanic cell method. At any experimental condition measurements were repeated at least three times for each configuration and the uncertainty was estimated to be about ±4% PPM for NO and ±10% for CO emission. For imaging the OH* chemiluminescent intensity distribution, an ICCD camera coupled to a narrow band filter having center wavelength of 310 nm wavelength was used. The resulting OH* intensity distributions were then normalized to the same scale.

To control the combustor pressure, a valve was added at the exit port. The pressure inside the combustor was controlled to ±0.007 atm (±0.1 psi) of the desired value. The pressure was measured inside as well as upstream of the combustor. Fig. 2 shows the test combustor with air and fuel injection locations, pressure measurement points, and control valve at the exit.

3. Experimental condition

Experiments were performed in two phases. In the first phase, the combustor pressure was increased while keeping the mass flow rate constant (heat load constant). Increasing the combustor pressure increases the reactants density and the flow velocity is decreased. Under these conditions, the apparent residence time in the combustor is increased. The apparent residence time can be defined as the volume of the combustor divided by the volumetric flow rate of the reactants. Also the energy (heat) release intensity (defined as the amount of energy released per unit volume per unit pressure, also known as heat release intensity or HRI) is affected. Table 1 gives the reported pressures along with the apparent residence time and energy (heat) release intensity for the respective phase.

In the second phase, the mass flow rate was increased with increase in pressure to result in constant apparent residence time and heat release intensity (HRI). Such increase in mass flow rate resulted in an increase in the heat load of the combustor. Table 2 gives the experimental conditions.

4. Results and discussion

4.1. Constant mass flow rate

The experiments were carried out for the impact of increase in combustor pressure on pollutants emission. The mass flow rates of air and fuel were kept constant for all the pressures examined. This
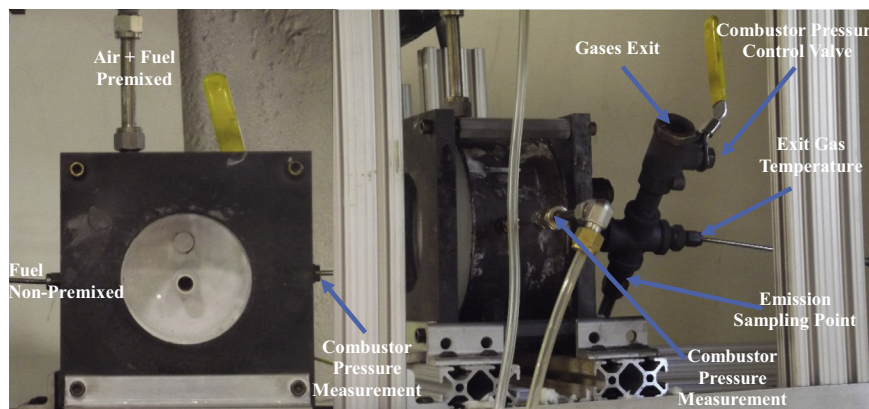

Fig. 2. Test combustor, left: front view showing injection points and pressure measurement point, right: combustor side showing pressure control valve and emission sampling point.

Table 1
Experimental parameters for constant mass flow rate condition.

Run	1	2	3	4	5	6
Configuration	ATP	ATF1	ATP	ATF1	ATP	ATF1
Heat load	4.7–6.25	4.7–6.25	5.47	5.47	4.7–6.25	4.7–6.25
Equivalence ratio	0.6–0.8	0.6–0.8	0.7	0.7	0.6–0.8	0.6–0.8
Pressure (atm)	1	1	1	1	2.35	2.39
			1.46	1.47		
			1.72	1.73		
			2	2		
			2.18	2.18		
			2.35	2.39		
Apparent residence time (ms)	70	70	70	70	166	169
			100	104		
			122	122		
			146	146		
			155	155		
			166	169		
Heat release intensity (HRI) (MW/m³ atm)	27–36	27–36	31.5	31.5	11.5–15.4	11.5–15.4
			21.6	21.4		
			18.3	18.2		
			15.3	15.3		
			14.4	14.5		
			13.4	13.2		

Table 2
Experimental parameters for constant heat release intensity (HRI).

Run	7	8	9	10
Configuration	ATP	ATF1	ATP	ATF1
Heat load	5.47	5.47	9.6–12.9	9.6–12.9
	8	8		
	8.7	8.7		
	9.4	9.4		
	10.4	10.4		
	11.3	11.3		
	12	12		
		13.3		
Equivalence ratio	0.7	0.7	0.6–0.8	0.6–0.8
Pressure (atm)	1	1	2	2
	1.46	1.46		
	1.59	1.6		
	1.71	1.72		
	1.9	1.9		
	2.08	2.03		
	2.18	2.19		
		2.46		
Apparent residence time (ms)	70	70	70	70
HRI (MW/m³ atm)	31.5	31.5	27–36	27–36

led to the apparent increase of residence time with increase in pressure due to the increase in reactants density and decrease in volumetric flow rate. Fig. 3 shows NO and CO emissions for different pressures examined at a constant equivalence ratio of 0.7 under premixed combustion. The results are plotted after being normalized by the NO and CO emissions at atmospheric pressure.

From Fig. 3, one can clearly see the impact of pressure on emissions. NO increases significantly with increase in pressure ($\propto P^{2.88}$). Measured NO emission increased significantly from about 2 PPM at atmospheric pressure to 16 PPM at 2.4 atm. Though the regression coefficient is low (0.87), this form is chosen to match other expressions found in the literature [18]. NO emission is seen to increase with increase in pressure over the range of pressures examined. Examination of the combustor performance at even higher pressures will provide us the improved correlation on the effect of pressure on emissions. Our future plans aimed at performing experiments at higher pressures using a different facility, will help clarify the extent of NO emission increase.

On the other hand, CO was significantly reduced with increase in pressure ($\propto P^{-2.82}$), from 140 PPM down to 20 PPM at a pressure of 2.4 atm. The high power of the correlation relating emissions to pressure outlines the significant impact of pressure on emissions. However, the increase in NO and decrease in CO emissions did not only result from the increase in pressure but also can result from increase in the apparent residence time. Increasing the pressure at constant mass flow rate decreases the volumetric flow rate and injection velocity, and increases the apparent residence time. To examine the role of residence time, the same data is plotted versus the apparent residence time (instead of pressure). The results are shown in Fig. 4.

In this case the correlation showed that NO increased with a power of 2.33 (instead of 2.88) and CO decreased with a power of -2.39 (instead of −2.82). The emissions performance with respect to residence time agrees with the work or Rutar and Malte [14], specifically for CO. The difference between both powers reveals that the residence time has a more significant impact on emissions as compared to increase in pressure.

To further explore these results, OH* chemiluminescence was recorded to characterize the reaction progress and correlate them with the obtained emissions. The OH* signatures are shown in Fig. 5 for premixed combustion mode. The change in the reaction zone with change in pressure reveals that the reaction moves upstream with increase in pressure. For atmospheric pressure, the reaction extends all over the combustor from the injection point and ends at about three quarters of a "turn" through the combustor. As the pressure increases, the reaction zone tends to end further upstream compared to the atmospheric pressure case (about half a turn for pressure of 1.72 atm and one quarter at 2.35 atm, see Fig. 5). The decrease in reaction length can be seen as a direct result of the decrease in injection velocity, where the reaction can stabilize itself further upstream. In a previous investigation, increase in injection velocity resulted in a spread of the reaction zone to occupy larger volume [10], indicating a direct proportionality between injection velocity and reaction zone size. The same behavior can be seen here, where lower velocities result in a smaller reaction zone, indicating the presence of concentrated flame zone along with local hot spots that results in higher NO as seen through emissions data shown in Figs. 3 and 4 along with the increase in the residence.

The experiments were repeated for non-premixed combustion mode at constant mass flow rate. The emissions data are shown in Fig. 6. CO emissions were reduced with increase in pressure ($\propto P^{-2.3}$) which is near the value experienced with premixed combustion ($\propto P^{-2.82}$). This reduction in CO emissions in both premixed
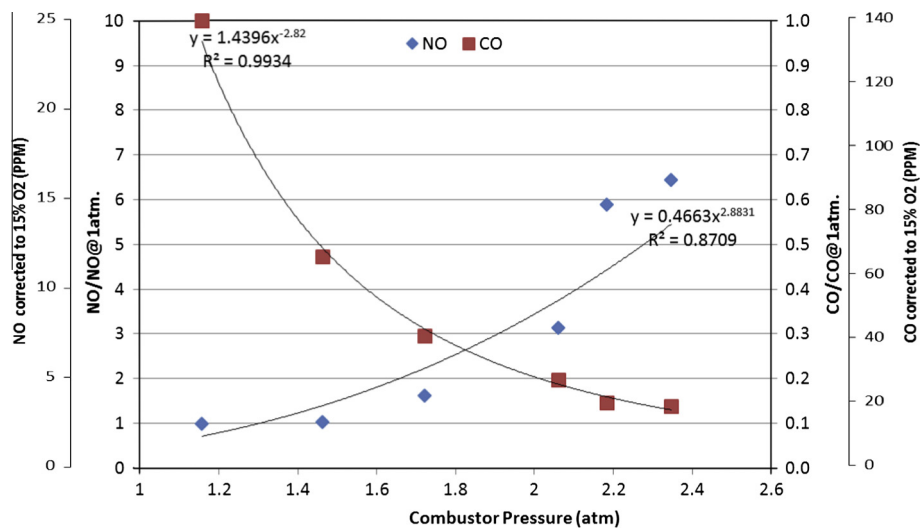
Fig. 3. NO and CO emissions corrected to 15% O_2 and normalized by emissions at atmospheric pressure for the different pressures at an equivalence ratio of 0.7 under premixed combustion mode.
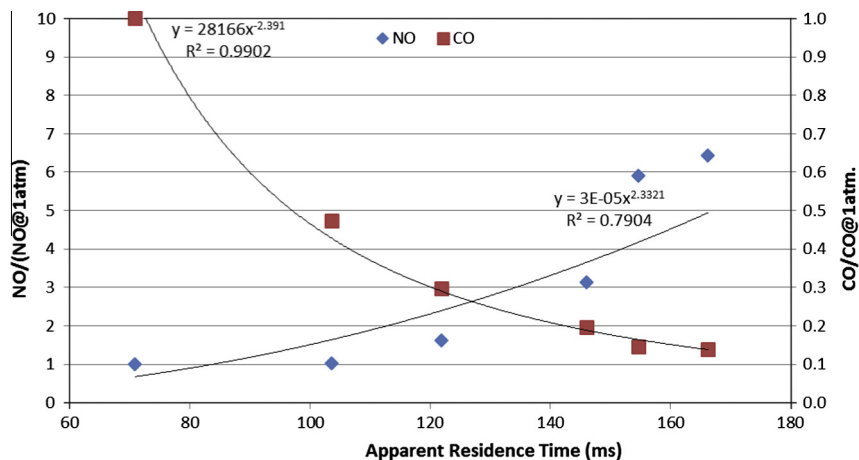

Fig. 4. NO and CO emissions normalized by emissions at atmospheric pressure for the different apparent residence times at an equivalence ratio of 0.7 under premixed combustion mode.
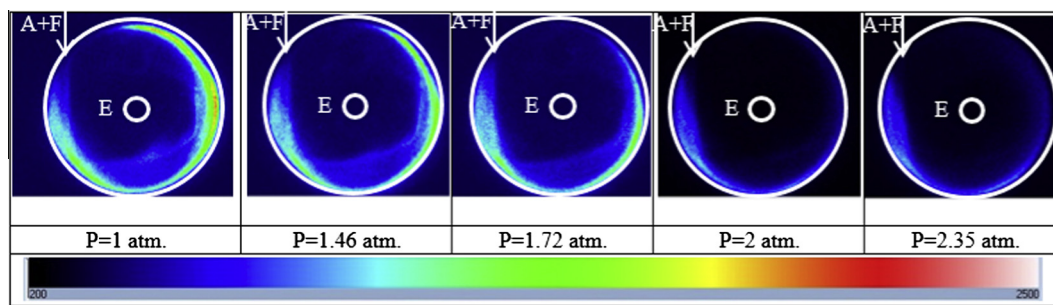

Fig. 5. OH* chemiluminescence for the different pressures examined under premixed combustion mode at an equivalence ratio = 0.7.

and non-premixed combustion mode is a result of the increased residence time at increased pressure. Increase in pressure enhances chemical reaction kinetics to accelerate the conversion of CO to CO_2. Also dissociation is suppressed as high pressure favors CO_2 over CO and O_2 [19]. On the other hand, NO emissions increased with increase in pressure/residence time; however, the power dependency is different. The emissions had a lower dependency on pressure ($\propto P^{1.49}$) as compared to premixed combustion

mode ($\propto P^{2.88}$). This change in behavior dependency from 2.88 to 1.49 indicates that other than pressure and residence time, mixing plays an important role. Under premixed combustion and atmospheric pressure, mixing between air, fuel, and hot recirculated gas was adequate enough to result in distributed combustion conditions (as seen from the ultra-low NO emission of 2 PPM). As the pressure was increased, mixing was not adequate, as the reaction zone moved further upstream with limited recirculation of hot
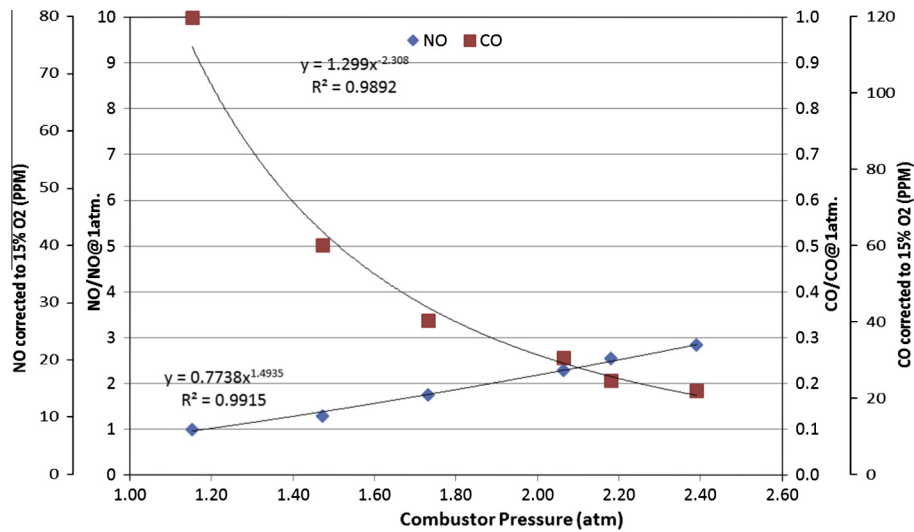
Fig. 6. NO and CO emissions corrected to 15% O_2 and normalized by emissions at atmospheric pressure for the different pressures at an equivalence ratio of 0.7 under non-premixed combustion mode.

reactive gases due to the lower injection velocity, resulting in a drastic increase in NO with an exponent of 2.88. This was not the case for non-premixed combustion. NO emission was about 8 PPM at atmospheric pressure, much higher than that measured for premixed combustion (2 PPM). This lack of adequate mixing (and high emissions) at atmospheric pressure for the non-pre-mixed case was further impacted by the decrease in injection velocity. As the injection velocity is decreased (due to increase in pressure), the turbulence levels are lower in the injection region. For the jet momentum ratio between air and fuel jets in this com-bustor, mixing is significantly impacted by turbulence levels and any decrease in turbulence level significantly impacts the mixing process. The opposite of this is true as well, any increase in turbu-lence leads to a better mixing under the examined conditions [10,20,21]. This explains the increase in NO emissions with pres-sure in the non-premixed case, but does not justify the difference in NO emission exponents.

Fig. 7 shows the OH* Chemiluminescence for the non-premixed case. The OH* chemiluminescence zone shifted upstream with increase in pressure, where the separation distance between the fuel injection point and the start of the OH* zone was reduced with increase in pressure. Also the maximum OH* chemiluminescence intensity shifted upstream with increase in combustor pressure. This behavior is attributed to the lower injection velocities at higher pressures. Although the reaction zone moved upstream with pressure, it only starts after the fuel injection point, leaving enough time for air and hot recirculated gases to mix together prior to fuel introduction and reaction initiation. This feature was not present in premixed combustion, where reactants ignited

without adequate mixing with hot recirculated reactive gases. In other words, for premixed combustion, increasing the pressure shifted the reaction zone upstream preventing adequate mixing between air/fuel and the hot recirculated gases prior to ignition. On the other hand, for non-premixed combustion, increasing the pressure shifted the reaction upstream towards the fuel injection point without affecting the mixing between air and the hot recircu-lated gases, resulting in adequate mixing between air and the recir-culated gases but inadequate mixing with fuel. This difference in mixing between premixed and non-premixed combustion explains the difference in the exponent power for NO emissions (1.49 vs 2.88).

For both premixed and non-premixed combustion, the longer residence time (through lower volume flow rate leading to higher apparent residence time) contributes significantly to the rise seen in NO emissions. Biagioli and Guthe [16] found that prompt NO_x decreases with increase in pressure, however, post-flame NO_x (including thermal NO_x) increases with pressure. The early reaction seen through OH* signature (see Fig. 5 and 7) gives more time for slow reacting post flame NO_x due to the more time available after the reaction, along with the longer residence time in the combus-tor from the increase in pressure (density) to result in lower flow rate.

4.2. Constant energy (heat) release intensity

To examine the impact of pressure without changing the resi-dence time, both the pressure and mass flow rates were increased to result in a constant energy (heat) release intensity and constant
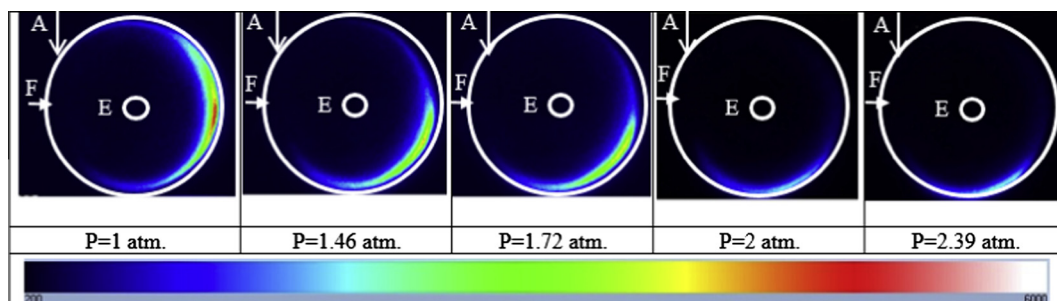

Fig. 7. OH* chemiluminescence for the different pressures examined under non-premixed combustion mode at an equivalence ratio = 0.7.

apparent residence time. That led to a significant increase in the combustor heat load from 5.47 kW to 13.3 kW.

Fig. 8 shows NO and CO emissions under premixed mode (normalized to emissions at atmospheric pressure). The results show that for the pressures examined here the NO emission increase by about 47% between atmospheric pressure and 2.2 atm (or from 2.4 to about 3.5 PPM of NO). The increase of NO with pressure had a proportionality of $P^{0.734}$ which is significantly lower than the value recorded in the constant mass flow rate case ($P^{2.88}$). The slight increase in emission can be a result of the increased combustor heat load (from 5.47 kW at 1 atm to 11.3 kW at ~2.2 atm) which leads to overall higher temperatures in the combustor (as seen through measured product gases exit temperature, where exit temperature increased by 15% between $P = 1$ atm and $P = 2.2$ atm). On the other hand, the CO emission was significantly reduced with increase in pressure with a proportionality of $P^{-2.149}$. Emissions were reduced from 90 PPM to 25 PPM. The power dependency value (-2.149) is lower than that recorded in constant mass flow rate case (-2.82). As explained earlier this value of -2.82 results from increased pressure and increased residence time (which had a power dependency of -2.39 as shown in Fig. 4). In this set of experiments there is no increase in residence time so that one would not expect much reduction in CO emission. However, the increase in heat load and increase in temperature significantly contributes to CO reduction as higher temperature aids in CO to CO_2 conversion [19].

The reaction behavior was also captured through OH* chemiluminescence at constant HRI. One can see no noticeable change of the OH* intensity distribution with increase in pressure (see Fig. 9). The reaction zone took the same shape for all the pressure reported with almost no change in the intensity distribution or intensity values. This behavior confirms that the reason behind the increase of emissions encountered in the constant mass flow rate case is a result of the reduced injection velocity and longer apparent residence time in the combustor with minimal impact of increasing pressure.

The NO and CO emissions were also recorded under non-premixed combustion mode. These emissions were normalized by emissions at atmospheric pressure and are shown in Fig. 10. The CO emissions decreased with increase in pressure as shown for the premixed combustion case with a slightly higher dependency on pressure ($P^{-2.76}$ for non-premixed instead of $P^{-2.149}$ for premixed). On the other hand, NO emissions increased more than that of the premixed combustion mode. The normalized NO emissions increased with a proportionality of $P^{1.16}$ as compared to $P^{0.734}$ in premixed combustion mode. The NO emissions increased by almost 150% between atmospheric pressure and 2.5 atm. This indicates that the mixing between air and fuel along with recirculated hot reactive gases deteriorates with increase in pressure to result in hot spots and departure from CDC conditions. Not only increase of normalized emission was higher, but the absolute value of emissions was higher. NO emission was measured to be 29 PPM at
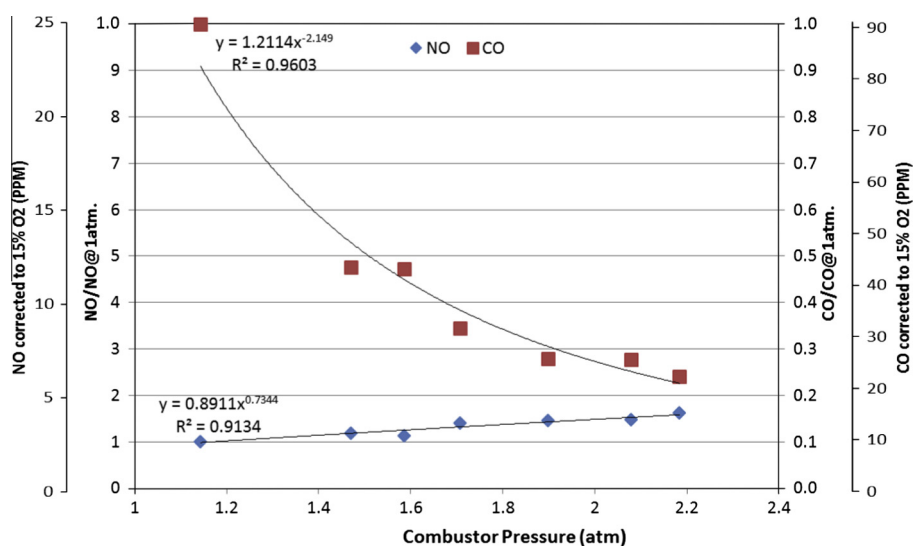

Fig. 8. NO and CO emissions corrected to 15% O_2 and normalized by emissions at atmospheric pressure for the different pressures at an equivalence ratio of 0.7 under premixed combustion mode for constant HRI.
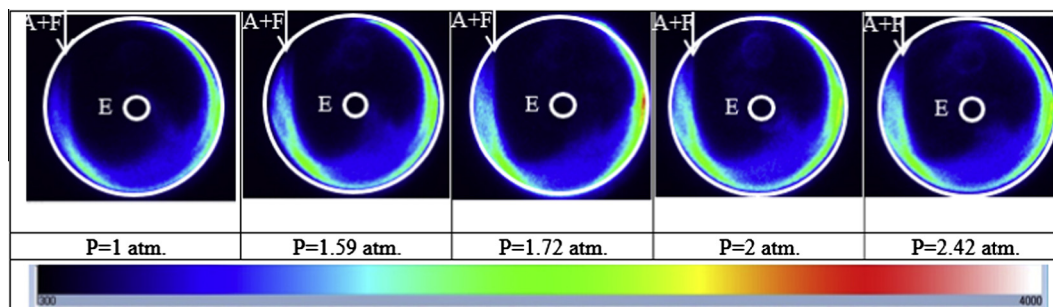

Fig. 9. OH* chemiluminescence for the different pressures examined under premixed combustion mode at an equivalence ratio = 0.7 for constant HRI.
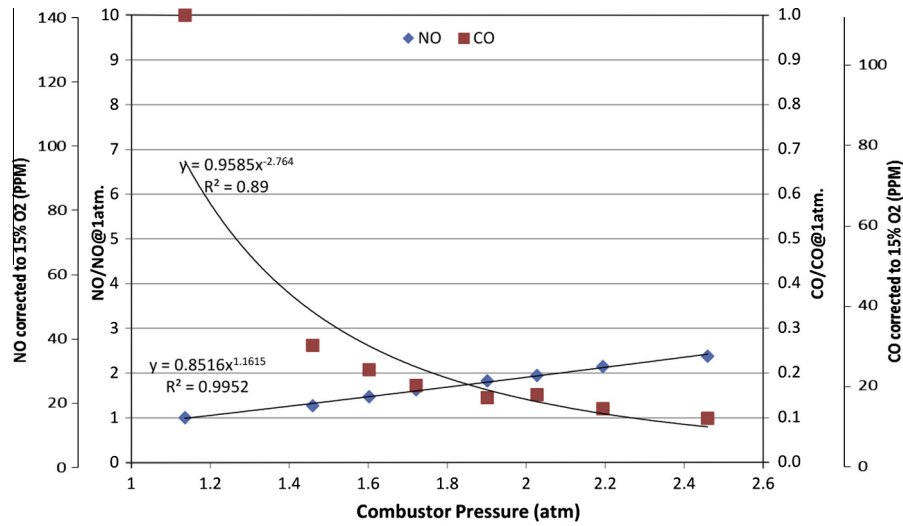
Fig. 10. NO and CO emissions corrected to 15% O_2 and normalized by emissions at atmospheric pressure for the different pressures at an equivalence ratio of 0.7 under non-premixed combustion mode for constant HRI.

2 atm, much higher than the 3.5 PPM recorded under premixed combustion mode for the same pressure. Previous researches have outlined that NO_x emissions increases significantly with the increase in unmixedness [16,17]. They examined degree of unmixedness up to a value of 0.08% [16], and 0.3% [17]. It is noteworthy that for non-premixed combustion, the injection is perfectly unmixed and the unmixedness takes a value of 100%.

The OH* chemiluminescence under non-premixed combustion was also captured to understand the behavior of the combustor under these conditions. These results are shown in Fig. 11. Increase in pressure results in almost similar reaction zone but the maximum intensity increased. This can be seen starting from atmospheric pressure up to 2 atm. Afterwards, the reaction moves downstream and forms a high concentrated OH* chemiluminescence zone. This is in contrast to premixed combustion case results shown in Fig. 9, where no noticeable difference between different OH* chemiluminescence intensity distribution was found for the pressures examined. The presence of the concentrated OH* region is seen to be the cause of this increase in NO and the higher dependency on pressure, which was not observed under premixed combustion mode.

This variation between premixed and non-premixed combustion mode behaviors requires further investigation on the mixing process at elevated pressures. Previous investigations of CDC demonstrated the possibility of achieving ultra-low NO emissions under non-premixed combustion provided that CDC conditions are achieved [1,2,10,11]. Increasing the combustor pressure, as seen in this investigation, resulted in less than adequate mixing for non-premixed combustion mode where CDC conditions were not achieved to result in high values of NO emission.

4.3. Extrapolation to higher pressures

Stationary gas turbines operate at pressures higher than those examined here. Pressure ratio for stationary gas turbines varies between 6 and 18 depending on the size, with much higher pressure ratios for aviation application. However, one can use the obtained relations between NO and operational pressure to predict the performance of the combustor at higher pressures. Equations for premixed combustion under constant HRI are as follows:

$$(NO/NO@1\,atm = 0.8911P^{0.7344}) \tag{1}$$

$$(CO/CO@1\,atm = 1.2114P^{-2.149}) \tag{2}$$

where NO@1 atm is the recorded NO emission at 1 atm, P is the operational pressure, and CO@1 atm is the recorded CO emission at 1 atm.

Using these relations, and assuming a combustor pressure of 16 atm, the obtained NO emission will be ~16 PPM (following Eq. (1), and measured NO@1 atm of 2.4 PPM). This value is at an equivalence ratio of 0.7 which is relatively high for stationary gas
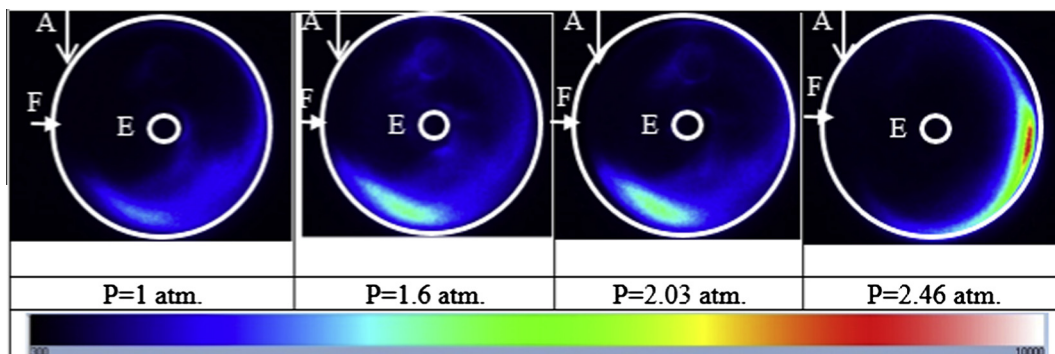

Fig. 11. OH* chemiluminescence for the different pressures examined under non-premixed combustion mode at an equivalence ratio = 0.7 for constant HRI.

Table 3
Measured and predicted emissions.

Emissions	Equivalence ratio = 0.7		Equivalence ratio = 0.6	
	NO (PPM)	CO (PPM)	NO (PPM)	CO (PPM)
P = 1 atm (measured)	2.4	90	1.2	266
P = 16 atm (predicted)	16.4	0.28	8.2	0.83

turbine operation. Using the same relation, the obtained NO emission will be about 8 PPM at an equivalence ratio of 0.6 with lower NO emission at lower equivalence ratios. Increasing the combustor pressure allows the combustion to occur at lower equivalence ratio to result in even lower emissions [2]. On the other hand, CO emission will diminish as the pressure increases. For a pressure of 16 atm, CO emission will be ~0.3 PPM (following Eq. (2) and measured CO@1 atm of 90 PPM) at an equivalence ratio of 0.7 and ~0.8 PPM at an equivalence ratio of 0.6. Table 3 sums these predicted emissions. These relations provide an insight on the role of pressure scaling on emission behavior. Further validation of these relations is required at even higher pressures to validate the trends. We expect the pressure trends to hold, albeit the accuracy may vary.

5. Conclusions

Experiments were performed on a model combustor at pressures between 1 and 2.5 atm. Results show the effect of pressure on NO and CO emission. Increase in pressure at constant mass flow rate resulted in a significant increase in NO emission and decrease in CO emission. This is attributed to the decreased volumetric flow rate (higher pressure increases density at constant mass flow rate), which in turn impacted the injection velocity to result in earlier flame stabilization and lower entrainment of recirculated hot reactive gases. The increased apparent residence time (as a result of the lower volumetric flow rate) also contributed to increase NO emission as longer residence times allow the formation of NO_x (post flame NO_x). The impact of lower injection velocity was demonstrated through OH^* chemiluminescence, where the OH^* intensity zone shifted upstream with increase in pressure as the flame was able to stabilize at lower velocities to allow the reaction to take place without proper mixing. The difference in emission behavior between premixed and non-premixed combustion outlines the importance of enhancing mixture preparation in non-premixed combustion where CDC conditions were not achieved at elevated pressures.

The impact of pressure without change in residence time was obtained by increasing mass flow rate with increase in pressure to result in constant energy (heat) release intensity and constant apparent residence time. NO emission increased slightly with increase in pressure. This increase can be attributed to the increase in pressure as well as the higher heat load of the combustor and the higher overall temperature of the combustor. The CO emission was significantly reduced at higher pressures as increasing pressure aids in CO to CO_2 conversion and suppresses dissociation. Also, the higher heat load and higher temperature aids in CO to CO_2 conversion (with the combustor mainly operated in the lean regime). OH^* chemiluminescence showed that the reaction did not change significantly with increase in pressure for premixed combustion. This behavior was not seen through non-premixed combustion, where the reaction intensity increased with increase in pressure then shifted downstream with a concentrated high

intensity region. This concentrated OH^* zone indicates the presence of thin concentrated flame front to result in high NO emissions. The difference between premixed and non-premixed behavior requires further examination to enhance the mixing process between air, fuel and hot reactive gases to achieve true colorless distributed combustion conditions for distributed reactions and near zero emissions.

Using the obtained relations, NO and CO emissions are predicted to be 8 PPM NO and 0.8 PPM CO at a pressure of 16 atm and a high equivalence ratio of 0.6 under premixed combustion operating under CDC conditions. Lower emissions are also possible at lower equivalence ratios.

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